

# Tough Question:

What will it take to identify the mechanism for baryogenesis or leptogenesis? Are there scenarios that could conceivably be considered to be established by experimental data in the next 20 years? What experiments are required to achieve this?

# Today's baryons are but a tiny remnant

- $10^8+1$  quarks for every  $10^8$  antiquarks created in the very early universe
- ***inflation would erase any initial asymmetry***
- Sakharov coined idea of ***baryogenesis*** in 1967 and proposed a model with three key ingredients (now known as Sakharov conditions)
  1. C violation and CP violation
  2. B violation
  3. out of equilibrium process in early universe (CPT guarantees  $B=0$  in equilibrium)

# Sakharov Conditions and the Standard Model

- ✓ C and CP violation (but not enough)
- ✓ Baryon number violation (electroweak anomalous nonperturbative field configurations known as *sphalerons*, which are common at very high temperature, above electroweak phase transition at 100 GeV)
  - ★ sphalerons conserve B-L → *Leptogenesis*
- ❑ Out of equilibrium (no phase transition for  $m_H=126$ )

# Baryogenesis Contenders

- 3 viable proposals which use Lagrangian of “pre-existing” models that were proposed for other reasons
  - ▶ Leptogenesis
  - ▶ Electroweak baryogenesis
  - ▶ Affleck-Dine baryogenesis
- A plethora of other viable proposals which involve theories invented primarily for the purpose of baryogenesis and in some cases baryogenesis/dark matter

# What will it take to identify the mechanism for baryogenesis or leptogenesis?

- Some luck on the mechanism!
  - Some models hide most of the definitive stuff at ultra high energy
    - high scale leptogenesis
    - Affleck-Dine
  - others have all the relevant particles and interactions at the weak scale
    - low scale leptogenesis
    - electroweak baryogenesis

Are there scenarios that could conceivably be considered to be established by experimental data in the next 20 years?

- YES
  - Electroweak baryogenesis
  - low scale leptogenesis
  - high scale leptogenesis with additional symmetries/constraints
  - Affleck-Dine with Q-ball dark matter
  - Baryosymmetric dark matter/baryogenesis with baryon destruction by dark matter

# Leptogenesis Models

- *high scale models predict light active neutrinos ( $< 0.1$  eV)*
- *high scale models inconsistent with low scale B-L violation (no neutron anti-neutron oscillations)*
- *high scale models require Majorana neutrinos*
- *CPV in oscillations (but phase not predicted in high scale models unless specific models with more symmetry considered)*
- *Traditional leptogenesis via decay of heavy  $(10^9-10^{10}$  GeV) neutrino requires high reheat scale after inflation*
  - *gravitino problem in susy*
- *models with lower energy leptogenesis, lighter particles more constrained and and testable*

# Affleck-Dine

- *requires supersymmetry (but does not predict spectrum)*
- *requires inflation with low scale*
  - ➡ *no inflationary B-modes*
- *Q-ball dark matter potential (but not necessary) smoking gun*
- *high (10 TeV) scale SUSY could give rare processes e.g.  $\mu \rightarrow e \gamma$*

# Electroweak Baryogenesis

- *Strongly first order electroweak phase transition*
- *new bosons strongly coupled to Higgs*
  - ➡ *top squarks (with susy CPV phases)*
  - ➡ *2HDM (with CPV in Higgs sector)*
  - ➡ *singlet + some new source of CPV*
- *Modified Higgs trilinear*
- *Visible Electric Dipole Moments (right around the corner!)*

# Other

- *traditional GUT baryogenesis needs to produce net  $B-L$  (else Baryon number washed out by sphalerons)*
  - ➡ *replaced by leptogenesis*
- *late gravitino decay*
  - ➡ *susy, heavy gravitino, RPV*
- *Baryosymmetric baryogenesis*
  - ➡ *Dark Matter is antibaryonic and destroys baryons*

# Relevant experiments for baryogenesis

- ➡ *search for B modes in CMB*
- ➡ *gravity wave search for evidence of 1st order PT*
- ➡ *axion dark matter search*
- ➡ *Q ball search*
- ➡ *exotic dark matter searches, e.g. asymmetric, anti B carrying..*
- ➡  *$0\nu\beta\beta$  decay*
- ➡  *$N_{\text{eff}}$  light relativistic species from CMB/LSS*
- ➡ ***CPV in  $\nu$  oscillations***
- ➡  *$\nu$  mass hierarchy*
- ➡ *absolute  $\nu$  mass*
  - *Katrin*
  - *Cosmology: LSS, CMB*
- ➡ *B violation, proton decay*
- ➡ ***EDM searches***
- ➡ *CPV and new flavor physics in meson mixing and decays*
- ➡ *search for new bosons at colliders e.g. light stop*
- ➡ *triple Higgs coupling measurement in colliders*
- ➡ *susy search in colliders, esp stealthy versions with near degeneracies*
- ➡ *indirect susy:  $\mu$  g-2,  $\mu \rightarrow e \gamma$ ,*
- ➡ *precision measurement of Higgs and new particle couplings*